METHOD AND APPARATUS FOR CONTROLLING WAVEGUIDE BIREFRINGENCE BY SELECTION OF A WAVEGUIDE CORE WIDTH FOR A TOP CLAD

TECHNICAL FIELD OF THE INVENTION

[0001]   The present invention relates generally to methods and apparatus for controlling waveguide birefringence. More particularly, the present invention relates to controlling waveguide birefringence by the selection of a waveguide core width for a given top cladding.

BACKGROUND ART OF THE INVENTION

[0002]   The increase in internet traffic and other telecommunications over the past several years has caused researchers to explore new ways to increase fiber optic network capacity by carrying multiple data signals concurrently through telecommunications lines. To expand fiber network capacity, fairly complex optical components have already been developed for wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM).

[0003]   Planar lightwave circuit (PLC) technology is one technology that may be used to implement optical wavelength routers. In a PLC, light is restricted to propagate in a region that is thin in two dimensions, referred to herein as the transverse dimension and the lateral dimension, and extended in the other dimension. In a conventional PLC, a core layer typically lies between a top cladding layer and a bottom cladding layer and channel waveguides are often formed by at least partially removing (typically through an etching process) core material beyond the transverse limits of the channel waveguide and replacing it with at least one layer of side cladding material that has an index of refraction that is lower than that of the core material. The side cladding material is usually the same material as the top cladding material.

[0004]   Each layer is typically doped in a manner such that the core layer has a higher index of refraction than either the top cladding or bottom cladding. When layers of silica glass are used for the optical layers, the layers are typically

1

deposited on a silicon wafer. Deposition processes include chemical vapor deposition (CVD), low pressure chemical vapor deposition (LPCVD), and/or plasma-enhanced CVD (PECVD). Moreover, one or more of the optical layers of the slab waveguide and/or channel waveguide may comprise an optically transparent polymer. For example, spin coating is one known film deposition method. A doped-silica waveguide is usually preferred because it has a number of attractive properties including low cost, low loss, low birefringence, stability, and compatibility for coupling to fiber.

[0005]　　　　The arrayed-waveguide grating router (AWGR) is an example of an integrated optical router. An AWGR is a PLC having at least one input channel waveguide, an input planar waveguide, an arrayed-waveguide grating (AWG), an output planar waveguide, and at least one output channel waveguide. Alternatively, an AWGR may comprise a plurality of output waveguides and a plurality of input waveguides. AWGRs may be configured to perform a variety of functions, for instance, they may function as multiplexers, demultiplexers, or they may be configured to perform both functions.

[0006]　　　　One aspect of performance that is affected by the present invention is referred to as polarization dependent wavelength (PDW). This term, as well as a number of related terms, will now be defined. Spectral transmissivity (in units of dB) is defined as the optical power (in units of dBm) of substantially monochromatic light that emerges from the fiber that is coupled to the input port minus the optical power (in units of dBm) of the light that enters the optical fiber that is coupled to the output port of the optical router. Spectral transmissivity is a function of the selected input port, the selected output port, the optical wavelength, and the polarization state of the incident light. When the incident light is in a polarization state called a "principle state of polarization," the light will be in the same polarization state when it emerges from the device. For purposes of illustration only, the principle states of polarization are assumed to be independent of wavelength, input port and output port. It is understood that the invention is not so limited by this assumption.

2

[0007] Again, for the purposes of illustration only, it will be assumed that the two principle states of polarization are the so-called transverse electric (TE) and transverse magnetic (TM) polarization states. The TE polarization state has an electric field that is predominantly aligned in the transverse direction and the TM polarization state has an electric field that is predominantly aligned in the lateral direction. Again, the invention is not so limited to devices having these principle states of polarization.

[0008] Typically, for values of spectral transmissivity that are larger than -10 dB, the TM spectral transmissivity is a replica of the TE spectral transmissivity that is shifted in wavelength by an amount that is referred to as the polarization dependent dispersion (PDD). PDD is positive if the TM spectral transmissivity has a maximum that has a longer wavelength than the maximum of the TE spectral transmissivity and is negative otherwise. PDW is defined as the absolute value of the PDD.

[0009] In many fiber optic communication systems, the polarization state of the light in the optical fiber may change in a manner that is uncontrolled and unpredictable. A change in the polarization state of the light in the fiber as it enters an AWG will cause a change in the optical power that emerges from the AWG that may be as large as the value of polarization dependent loss (PDL) for the AWG. There have been a number of techniques developed in an attempt to minimize PDW.

[0010] One approach to minimizing PDW involves selecting an optical layer design with minimum birefringence. In one example of this approach, U.S. Pat. No. 5,930,439 (Ojha *et al.*), which is incorporated herein by reference in its entirety, discloses a planar optical waveguide which reduces birefringence by doping the various optical layers so that the top cladding has a thermal coefficient of expansion that is close to the thermal expansion coefficient of the substrate.

[0011] Another approach is described in A. Kilian *et al.*, *Birefringence Free Planar Optical Waveguide Made by Flame Hydrolysis Deposition (FHD) Through Tailoring of the Overcladding*, Journal of Lightwave Technology, v. 18, no. 2, p. 193 (2000), which is incorporated herein by reference in its entirety.

Kilian discloses that because the thermal expansion of the top cladding largely determines the birefringence in the waveguide, a top cladding can be developed and made with a flame-hydrolysis-deposition (FHD) process to reduce the birefringence.

[0012]   Many methods and apparatus attempt to formulate a top cladding material which reduces birefringence. However, this may require specific compositions for the top cladding. These techniques, as well as others, teach the application of a specific top cladding composition to reduce birefringence. However, there is a need for a reliable method to reduce the birefringence in a waveguide for varying top cladding compositions.

SUMMARY OF THE INVENTION

[0013]   The top cladding material which usually covers the waveguides and substrate in an arrayed waveguide grating may determine in large part the resulting birefringence. However, given a top cladding composition, a width of the waveguide core may be pre-selected that provides a minimized birefringence, i.e., a zero, or near zero, polarization dependent wavelength. A tuned top cladding is used to describe a pre-existing dopant concentration within a top cladding material.

[0014]   In calculating the desired width of a waveguide core that provides the desired level of birefringence for a given tuned top cladding, the distribution of stress in the top cladding may be determined over a change in temperature. From this distribution of stress, a relationship may be determined between the polarization dependent wavelength and various widths of the waveguide in the arrayed waveguide grating. This relationship may determine a zero value, or near zero value, of polarization dependent wavelength for a given range of waveguide widths. PDW is a polarization dependent wavelength change and the wavelength change preferably ranges from about 0 ± 0.03 nm for the present invention to be optimized. The width of the waveguide may be selected such that the polarization dependent wavelength is minimized accordingly.

4

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Fig. 1 shows a variation on a cross-section of a substrate upon which a representative waveguide and top cladding may be disposed.

[0016] Fig. 2 shows an example of a chart where bi-directional stresses (MPa) in the top cladding are plotted against core width (μm).

[0017] Fig. 3 shows an example of a chart where the resulting PDW (nm) is plotted against core width (μm) to obtain a core width which may result in a PDW of zero.

[0018] Fig. 4 shows a flow chart of one variation on a method of determining a waveguide width for a given top cladding.

DETAILED DESCRIPTION OF THE INVENTION

[0019] The top cladding material which usually covers the waveguides and substrate may determine in large part the resulting birefringence. However, given a top cladding composition, a width of the waveguide core may be pre-selected that provides a desired birefringence. A top cladding which is "tuned" is used to describe a pre-existing dopant concentration within a top cladding material. That is, the top cladding is "tuned" to provide desired optical characteristics (such as a particular refractive index) but is not necessarily "tuned" to provide the lowest possible birefringence as described in Ojha *et al.* or A. Killian *et al.*

[0020] A representative cross-section **10** of a substrate with a waveguide and top cladding is shown in Fig. 1. As seen in this variation, cross-section **10** may have a substrate **12**, upon which waveguide **20** and top cladding **22** may be disposed. Substrate **12** may be comprised of up to several layers making up the substrate **12**. Layer **14** may be a layer of, e.g., undoped SiO_2 (silica), ranging in thickness from about 15-30 μm, but is preferably about 15 μm. The thickness of a layer in this example is taken as the distance along the y-axis; likewise, the width of a layer in this example is taken as the distance along the x-axis.

[0021] A silicon substrate **16** may be placed upon layer **14** and preferably has a thickness of about 625 μm. Then layer **18** (lower cladding) may be

deposited on silicon substrate **16** or formed by oxidizing the substrate in steam, for example. Layers **14** and **18** may be grown sequentially but are preferably grown simultaneously. Layer **18**, like layer **14** may be comprised of, e.g., undoped SiO_2 (silica), and may likewise have a thickness ranging from about 15-30 μm, but is also preferably about 15 μm.

[0022] A core layer may then be deposited on top of layer **18** using, e.g., standard silica deposition techniques such as flame hydrolysis or plasma-enhanced chemical vapor deposition (PECVD). This core material may be comprised of, e.g., silica with a dopant such as Germanium and/or Phosphorus, and may preferably have a refractive index about 0.5-1% higher than the lower cladding **18** index. Alternatively, the core material may comprise a variety of polymer materials such as optical grades of polyacrylates, polymethacrylates, polysilicone, polyimide, epoxy, polyurethane, polyolefin, polycarbonate, polyamides, polyesters, etc., as well as a various copolymers thereof, such as acrylate-methacrylates, acrylic-silicones, epoxy-urethanes, amide-imides, etc. The core layer may range in thickness, h, from about 5-8 μm, but is preferably about 6 μm thick. The core layer may be patterned using, e.g., photolithography and reactive ion etching, and an intermediate hard mask layer, such as chrome may be used, to define a waveguide core **20** preferably having a rectangular cross section. Waveguide core **20** also has a width, w, which may be varied accordingly to reduce the birefringence, as described below in detail.

[0023] After core **20** is etched, a silica top cladding layer **22** may be deposited on the structure. Although top cladding **22** may be comprised of specified compositions to reduce birefringence, as discussed above, this may be an unreliable method because of the difficulty in producing a top cladding composition which yields the required physical properties. A typical top cladding **22** may be comprised of, e.g., SiO_2 doped with Boron, but the concentration range of such dopants may be limited. For example, a top cladding **22** may be doped with, e.g., Boron, in a range of about 6-9% (wt.) because having a concentration of Boron below about 6% may yield glass which is too viscous for manufacturing and a concentration of Boron above about 9% may yield glass which crystallizes.

6

[0024]　　　As part of the present invention, a table of illustrative material properties, i.e., elastic modulus, E, and coefficient of thermal expansion (CTE), are shown below in Table 1 for the purposes of discussion.

Table 1. Example of material properties in a variation of a waveguide.

Waveguide element	E (GPa)	CTE (x 10^{-6} °C^{-1})
Top cladding	44	*
Waveguide core	62	2
Silicon (substrate)	200	3.5
Undoped SiO$_2$	70	1

* Discussed below.

[0025]　　　During the manufacture of an AWG, the layers of material are typically produced at elevated temperatures or they may require high temperature treatment to ensure homogeneity. Processing temperatures may be as high as about 900° C. Upon cooling, stresses may become induced into the waveguide core **20** because of the differing CTE values between, e.g., layer **18** and top cladding **22**, thereby resulting in undesired birefringence in light carried through core **20**. According to the invention, varying the width, w, of the waveguide core **20** may be selected to reduce or eliminate birefringence for a given tuned top cladding **22** having a pre-existing dopant concentration. The CTE mismatch from ambient temperature to a device operating temperature may typically be ignored for the purposes of the present invention because of the minimal effect such a temperature change may have.

[0026]　　　In calculating an optimal width for birefringence reduction for a given top cladding **22**, a stress value may be induced within core **20** in its blanket form. This stress value is typically due to a CTE mismatch between the film and the substrate and may result in a curvature within the plane of the substrate. This curvature may be measured and from there, the stress in the core film may be calculated by the following equation (1):

$$\sigma_{core} = \frac{E_{sub}(t_{sub})^2}{6Rt_{core}} \tag{1}$$

where,

σ_{core} = stress value induced in core **20** by a curvature of substrate **16**;

E_{sub} = elastic modulus of the substrate **16**;

t_{sub} = substrate thickness;

R = radius of curvature of a given wafer from which a device may be manufactured from according to the present invention;

t_{core} = waveguide core **20** thickness, h.

[0027]   In one variation, an example using the values as illustrated in Table 1 and t_{sub} = 625 μm in equation (1) may yield the following in equation (2):

$$\sigma_{core} = \frac{(200 \times 10^9)(625 \times 10^{-6})^2}{6(-22)(6 \times 10^{-6})} = -98 MPa \tag{2}$$

[0028]   Once calculated, the value of σ_{core} may be substituted into the following equation (3) to calculate the CTE value, α_{core}, of core **20**:

$$\alpha_{core} = \alpha_{sub} - \frac{\sigma_{core}}{E_{core}(\Delta T)} \tag{3}$$

where,

α_{core} = calculated CTE of core **20**;

α_{sub} = CTE of substrate **16**;

E_{core} = elastic modulus of core **20**;

ΔT = temperature range through which the materials undergo.

[0029]   Substituting the values from equation (2) and Table 1 may yield the following equation (4):

$$\alpha_{core} = (3.5 \times 10^{-6}) - \frac{-98 \times 10^6}{(62 \times 10^9)(-900)} \tag{4}$$

$$= 1.74 \times 10^{-6} \cong 2.0 \times 10^{-6} \,^\circ C^{-1}$$

8

These calculations may be performed for each individual layer within cross-section **10** to obtain the stress and CTE values of each layer.

[0030] A stress value of top cladding **22** induced by CTE differences over the temperature range ΔT, e.g., about 900° C from manufacturing/processing temperature to ambient temperature, may also be calculated. As discussed above, if top cladding **22** were doped with a high concentration, e.g., about 9% (wt.) of Boron, a tensile stress may be induced in top cladding **22**; on the other hand, if top cladding **22** were doped with a low concentration, e.g., about 6% (wt.) of Boron, a compressive stress or zero load may be induced in top cladding **22**. In calculating the stress, the following equation (5) may be used:

$$\sigma_{tc} = E_{tc}\left(-\alpha_{tc} + \alpha_{sub}\right)\left(\Delta T\right) \qquad (5)$$

where,

σ_{tc} = stress value induced in top cladding **22** by CTE differences between top cladding **22** and substrate **16**;

α_{tc} = CTE of top cladding **22**;

α_{sub} = CTE of substrate **16**;

E_{tc} = elastic modulus of top cladding **22**;

ΔT = temperature range through which the materials undergo.

[0031] Substituting in values from Table 1 for a variation where a top cladding **22** has a CTE of about, e.g, $\alpha_{tc} = 3.2 \times 10^{-6}\ °C^{-1}$, and undergoes a temperature change of about, e.g., $\Delta T = 900°$ C, may yield the following equation (6). Whereas, top cladding **22** having a CTE of about, e.g, $\alpha_{tc} = 4.0 \times 10^{-6}\ °C^{-1}$, may yield the following equation (7).

$$\sigma_{tc} = (44 \times 10^{9})(-3.2 + 3.5)(-900)(\times 10^{-6}) = -12\ MPa \qquad (6)$$
$$\sigma_{tc} = (44 \times 10^{9})(-4.0 + 3.5)(-900)(\times 10^{-6}) = 20\ MPa \qquad (7)$$

9

[0032]   As discussed above, a difference in effective index for the TE and TM polarization states is a reason for the occurrence of PDW, as expressed in equation (8):

$$PDW = \lambda_{c(TM)} - \lambda_{c(TE)} \tag{8}$$

where,

$$\lambda_c = \beta \frac{\Delta L}{m} \tag{9}$$

λ_c = wavelength of light through waveguide core **20**;

β = effective refractive index;

ΔL = distance traveled by the light through waveguide core **20**;

m = diffraction order.

Substituting equation (9) into equation (8) yields the following result in equation (10):

$$PDW = (\beta_{TM} - \beta_{TE}) \frac{\Delta L}{m} \tag{10}$$

[0033]   The difference between β_{TM} and β_{TE} may be a result of differing stresses in the x- and y-directions along waveguide core **20**. This difference may vary as the width, w, of core **20** varies. As seen in Fig. 2 in chart **30**, stress (in MPa) induced in top cladding **22** may be plotted against core width (in μm) to see the relationship. Curve **32** represents the increasing absolute value of stress, σ_x, along the x-axis as the width, w, of core **20** increases. On the other hand, curve **34** shows a decreasing stress state, σ_y, along the y-axis as the width of core **20** increases. The overall stress state between σ_x and σ_y is shown in curve **36**, where the stress state is shown to increase as core width increases.

[0034]   In practice, stress calculations and stress distributions may be complex and are preferably solved through the use of computer simulations, e.g., finite element modeling/analysis, which may account for geometry, differences in material properties, and external factors such as temperature changes and forces. Given the different CTE and stress values for each of the layers, as described

10

above, the stress distributions may be calculated over a range of varying core **20** widths, w, e.g., widths up to 11 μm and up. That is, thermal stress distributions in waveguide core **20** and surrounding cladding **22** may be calculated for each core **20** width over a range of widths.

[0035] Once the stress distributions are calculated, as described above, an index distribution may be calculated according to the following equations (11) and (12):

$$n_y\ (x,y) = n_{yo}\ (x,y) - c_1\sigma_y\ (x,y) - c_2\ [\sigma_z\ (x,y) + \sigma_x\ (x,y)] \qquad (11)$$
$$n_x\ (x,y) = n_{xo}\ (x,y) - c_1\sigma_x\ (x,y) - c_2\ [\sigma_y\ (x,y) + \sigma_z\ (x,y)] \qquad (12)$$

Constants c_1 and c_2 are stress optic coefficients where, e.g., $c_1 = 7.56 \times 10^{-7}$ MPa^{-1} and $c_2 = 4.18 \times 10^{-6}$ MPa^{-1}; and where, e.g., $n_{xo} = n_{yo} = 1.4455$ for top clad **22** and $n_{xo} = n_{yo} = 1.455$ for core **20**.

[0036] Properties such as refractive index can have complex distributions throughout a device and may be solved through computer simulation of the geometry, refractive indices, and absorption of the waveguide and cladding, as well as index change mechanisms, e.g. temperature changes, using commonly available photonic software such as BeamPROP, made by RSoft, Inc. of Ossining, NY. From such software tools and from the stress results and stress distributions, the effective refractive index may be found. With the results of refractive index distribution according to equations (11) and (12), the effective refractive index β may be calculated using, e.g., the BeamPROP simulation. This may be performed at least once for the TE mode (n_x distribution) and at least once for the TM mode (n_y distribution). Once the results of β_{TM} and β_{TE} have been calculated, PDW may finally be calculated with equation (10).

[0037] An example of another method of PDW reduction which varies the lengths of the relevant waveguides as well as utilizes the results of β_{TM} and β_{TE} may be found in the commonly-assigned U.S. Patent Application entitled "Arrayed Waveguide Grating With Waveguides Of Unequal Widths" to Kenneth

McGreer, filed on May 30, 2001 and which is incorporated herein by reference in its entirety.

[0038]   Fig. 3 illustrates the relationship in chart **40** between PDW (in nm) and core width (in μm) for a top cladding having several different CTE values. Curve **42** represents a variation where a top cladding **22** has a CTE of about 4.0 x 10^{-6} °C^{-1} and a resulting σ_{tc} equal to about 20 MPa for a ΔT of about 900° C. Curve **46** represents another variation where top cladding **22** CTE is about 3.6 x 10^{-6} °C^{-1} and a resulting σ_{tc} equal to about 4 MPa. Likewise, curve **48** represents yet another variation where the CTE of top cladding **22** is about 3.2 x 10^{-6} °C^{-1} and a resulting σ_{tc} equal to about -12 MPa. As seen, as top cladding **22** CTE is lowered below that of substrate **16** (where CTE is about 3.5 x 10^{-6} °C^{-1} in this variation), PDW generally increases. Data points **44** represent experimental results and are shown to show the close approximation and validity of the methods described above.

[0039]   Boundary **50** represents a state where PDW is zero. Accordingly, for every top cladding **22** process, e.g., a high Boron concentration and high CTE or a low Boron concentration and low CTE, a corresponding width, w, for waveguide core **20**, such as the width corresponding to intersection **52**, may be found that results in a zero PDW state.

[0040]   As described above, in calculating a width of a waveguide core that provides a desired birefringence for a given tuned top cladding composition, the distribution of stress in a top cladding over a change in temperature may be determined. From the distribution of stress, a relationship may be determined between polarization dependent wavelength and a width of the waveguide in the arrayed waveguide grating. From this relationship, the width of the waveguide may be selected such that the polarization dependent wavelength is minimized or reduced to a desired value to compensate for birefringence.

[0041]   A flow chart **60** is shown in Fig. 4 for one variation on a method of determining waveguide width for a given top cladding. Operation **62** may begin by determining an elastic modulus of each of the constituent layers, e.g., layers **14** to **22**. This may be accomplished by measuring the modulus directly. Operation

12

64 may follow where a stress value may be determined in each of the layers, e.g., layers **14** to **22**. In operation **66**, the CTE values of each of the layers may be calculated by a method as described above. Operation **68** may follow where a stress distribution may be calculated in, e.g., core **20** and top cladding **22**, for various core widths, w, to determine a thermal residual stress distribution due in part to CTE mismatches between different material types. Such calculations may be performed by computer simulations using, e.g., finite element modeling/analysis tools.

[0042] Operation **70** may follow where the stress distribution calculated in operation **68** may be mapped into an index distribution using a conventional stress optic coefficient. The index distribution may be determined by any of the methods as described above. Operation **72** may follow where an effective index of core **20** and top cladding **22** may be determined by simulations using, e.g., photonic software such as BeamPROP. From the results of operation **72**, a PDW may be calculated in operation **74** by a method as described above. Operation **76** may follow where a relationship between PDW and various core widths, w, may be determined by, e.g., plotting the results on a chart as described above. An appropriate core width may accordingly be selected in which PDW is minimized, i.e., results in zero, or near zero within about 3%, PDW for any given top cladding material by utilizing the methods described above.

[0043] The applications of the methods and apparatus discussed above are not limited to the numerical examples given or to the disclosed materials having specific CTEs, but may also include any number of further applications, e.g., different material types, different CTE values, etc. Modification of the above-described methods and apparatus for carrying out the invention, and variations of aspects of the invention that are obvious to those of skill in the art are intended to be within the scope of the claims.